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Determining Resistivity Anisotropy By Joint Lateral And Induction Logs

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ABSTRACT

Real geological formations may exhibit resistivity anisotropy in two ways: micro-anisotropy and macro-anisotropy. Micro-anisotropy is intrinsically anisotropic because of the microstructure of the formation. However, macro-anisotropy is often due to electrical and electromagnetic well logging methods can achieve only limited resolution of the resistivity layering, for example, we often have to consider a collection of many thin layers as one composite layer, which is then macro-anisotropic. Macro-anisotropy is also found in cases of a fractured formation. In this paper, it is assumed that the resistivity is the same in all horizontal directions, but is different in the vertical direction, i.e. a transversely isotropic layered model.

The determination of resistivity anisotropy is desirables as it may indicate the presence of otherwise unresolved thin layers and fractured formations. From a hydrogeological point of view, these may severely influence the hydraulic flow pattern in the ground. Thin clay layers in an otherwise sandy formation will lower the vertical hydraulic conductivity considerably and will deflect infiltration, and thin sand and gravel layers in an otherwise clayey formation may be serve as fast hydraulic conduction channels for polluted water.

Three-component induction well logging may be the best method to determine the resistivity anisotropy. However, the tool has still not used in China. All data are typical lateral and dual induction logs. Neither lateral well logging methods nor inductive well logging methods alone can resolve the anisotropy of the formation. However, a joint inversion of lateral and inductive data makes that anisotropy be taken into account and it can also resolve the coefficient of anisotropy, thus contributing to a more detailed description of the formation resistivity.

In this paper, an analysis of the importance of taking anisotropy into account in inverse modeling is presented, and it is shown how the combined use of lateral and inductive logs can resolve the coefficient of anisotropy of a formation. Through a synthetic 2D model, we show that inductive methods will only sensitive to the horizontal resistivity of a layer, while the thickness is undistorted. That is to say, we can determine the horizontal resistivity and formation thickness by inductive methods, but we can not determine the vertical resistivity by inductive methods, thus we cannot determine the coefficient of anisotropy. However, apparent resistivity of lateral methods can be approximate as the geometry mean resistivity of horizontal and vertical resistivities. And apparent thickness of lateral methods is the multiplication of anisotropy coefficient and real thickness. Therefore we can not determine any parameters alone by lateral logs. However, a joint inversion of data from lateral and inductive logs may determine three parameters: the coefficient of anisotropy, horizontal resistivity and formation thickness. Synthetic data show that the joint inversion method is feasible.

INTRODUCTION

Resistivity logs are the most important methods to determine values of residual and movable hydrocarbon saturation. However, The effects of

hydrocarbon saturation. However, The effects of anisotropy make that the logs can not response the full and true information of formation resistivities. For example, induction loggings only response the horizontal resistivites in vertical well. To get horizontal and vertical resistivities of formation ones need to joint different logs. T.Hagiwara et al. (1999) identified and quantified resistivity anisotropy by joint induction and laterolog logs. However, we have found laterolog logs are almost only sensitive to horizontal resistivity in vertical well since the function of the focus electrodes. Niels B. Christensen (1999) presnted the ability of the joint inversion of geoelectrical and transient sounding data to resolve macro-anisotropic layers and tested the results using realistic earth models determinded from electrical logs. Therefore, his paper enlightens us to use lateral logs.

This paper presents the possibility to resolve resistivity anisotropy by joint induction and lateral logs. At the following, we first give theory basis, then discuss results of numerical simulations, finally, give some discussion and conclusion.

THEORY

To lateral logging, an anisotropic layer is equivalent to an isotropic layer of thickness h_{LAT}, equal to the product of the coefficient of anisotropy and the true thickness, and of resistivity ρ_{LAT}, equal to the mean resistivity (Keller and Frischknecht 1966), so that

$$h_{LAT} = \lambda \cdot h \qquad (1)$$

$$\rho_{LAT} = \lambda \cdot \rho_h = \sqrt{\rho_v \cdot \rho_h} = \rho_m \qquad (2)$$

Herein, ρ_v, ρ_h is vertical and horizontal resistivity respectively. The coefficient of anisotropy λ is defined by $\lambda = \sqrt{\rho_v / \rho_h}$, h is the true thickness.

From the formulae (1) and (2) we cannot determine not only the coefficient of anisotropy λ, but also the true thickness h.

To induction logging, it only responses horizontal resistivity of a layer, while the thickness is undistorted, so that

$$h_{IND} = h \qquad (3)$$

$$\rho_{IND} = \rho_h \qquad (4)$$

From the formulae (3) and (4) we can get the true thickness h and horizontal resistivity ρ_h of a layer directly when neglecting the borehole, should and invasion effect. However, we still cannot determine the coefficient of anisotropy. Therefore, we cannot resolve the full resistivity information by induction or lateral logging separately.

However, we can first resolve the true thickness h and horizontal resistivity ρ_h by induction log. Then, to substitute h and ρ_h into (2), we can resolve the coefficient of anisotropy λ. Thus we can get the horizontal resistivity, the coefficient of anisotropy and the thickness of each layer by joint iversion of induction and lateral logs.

NUMERICAL SIMULATION

First, we assume a 2D three-layer formation model. The parameters in each layer are labeled in Fig 1a. In Fig 1a, we only change Rt-v. Rt-v is set as 10,100,1000,and 10000. The response results are shown in Fig 1b. It is 0.5m lateral log. We can see that lateral logs have a certain extent sensitive to resistivity anisotropy. In addition, in fig 2a, we only change Rt-h. Rt-h is set as

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10,100,1000,and 10000. The response results are shown in fig 2b. W can see that lateral logs are more sensitive to the change of horizontal resistivity. From fig 1b and fig 2b, we can make a conclusion that lateral log responses the change of Rt-h and Rt-v at the meantime. Therefore, lateral log can be used to resolve the coefficient of anisotropy λ when jointing with induction log.

To present the possibility, we firstly assume a 2D three-layer formation model. The parameters in each layer are labeled in Fig 3a. Next, we can get the synthesized lateral and induction logs by applying the relevant forward modeling codes. The synthesized curves are shown in fig 3b and 3c. The induction log is the response of standard dual induction tool. Therein, Rild is apparent resistivity of deep induction log and Rilm is apparent resistivity of middle induction log.

First, we can read the formation position is 4.25-6.25m and the true thickness h=2m from fig 3b of induction logs directly.

Next, the horizontal resistivity ρ_h can be resolved by inversion of induction logs. The layering of Rilm can be chosen as the initial value of ρ_h. The initial value of 3 layers is chosen as 2.1, 1.08, 2.1 respectively. After 3 iterations we almost get the true value of Rt-h. The result is shown in fig 4a. Inversion result has a good precision comparing with synthesized curve. Through inversion we can eliminate the effects of mud and shoulder.

Then, we substitute h and ρ_h into inversion process of lateral logs. We can resolve the coefficient of anisotropy λ only after the inversion. The results are shown in fig 4b. We have got Rt-v as 8.5 only after 3 interations. Then λ is 2.9154. Its true value is 3.162. The quality comparison result is shown in fig 4c.

Finally, we have got the horizontal resistivity, the coefficient of anisotropy and the thickness of each layer by joint inversion of induction and lateral logs.

DISCUSSION AND CONCLUSION

The research shows that lateral logs have information about horizontal and vertical resistivities. In addition, induction log can provide the true thickness of formation and horizontal resistivity alone. Therefore, we can identify and quantify resistivity anisotropy by joint lateral and induction log.

It is essential to inverse induction and lateral logs respectively to remove the effect of mud and shoulder.

If there are multi-parameters to be inverted we have to use multi logs such as Rild and Rilm.

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ABOUT THE AUTHORS

Wei Yang is an associate professor with University of Petroleum at Beijing after he finished his post-doctor research at there in June 1997. His main research interests are electromagnetic modeling and inversion, cross-well tomography, and mathematics application in geophysics, especially in electrical well logging. He received his BS, MS, and Ph.D. degrees in applied mathematics, numerical analysis, and general mechanics in Harbin Institute of Technology in 1989, 1992, 1995, respectively. (Email: weiyang@www.bjpeu.edu.cn)

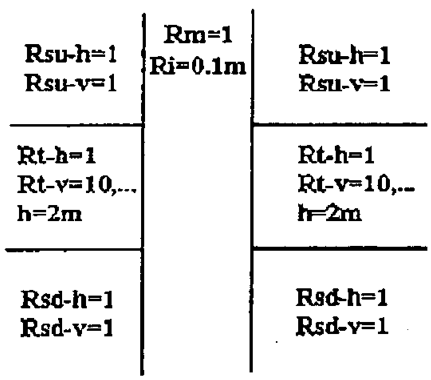

Fig 1a Formation model with change of Rt-v

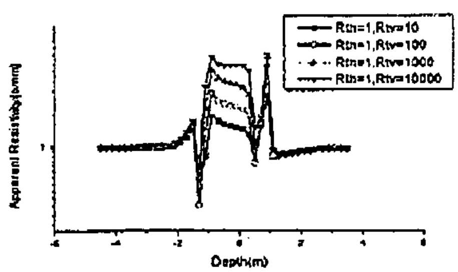

Fig 1b Lateral log with change of Rt-v

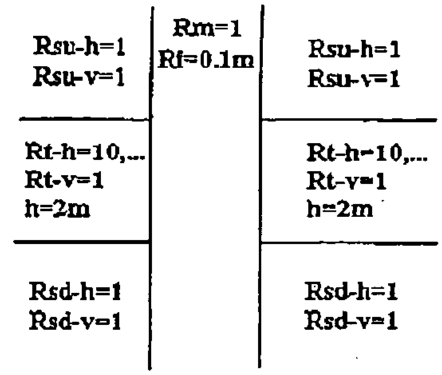

Fig 2a Formation model with change of Rt-h

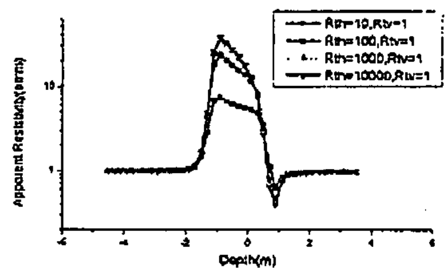

Fig 2b Lateral log with change of Rt-h

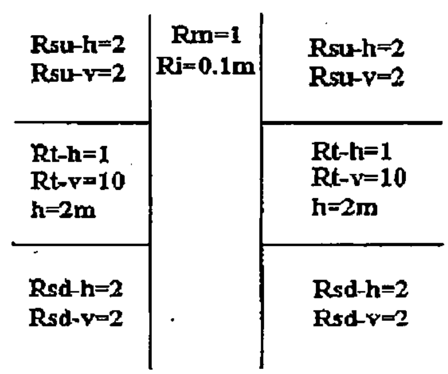

Fig 3a Formation model

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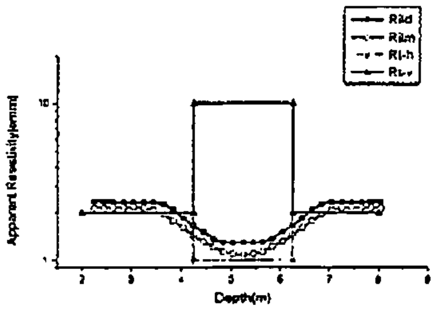

Fig 3b Induction log

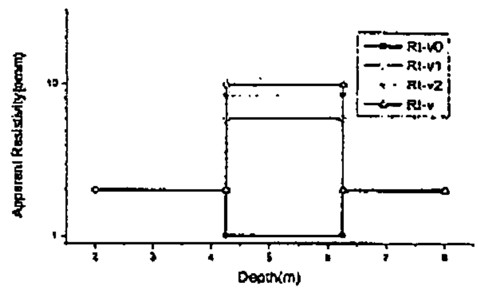

Fig 4b Inversion results of vertical resistivity Rt-v

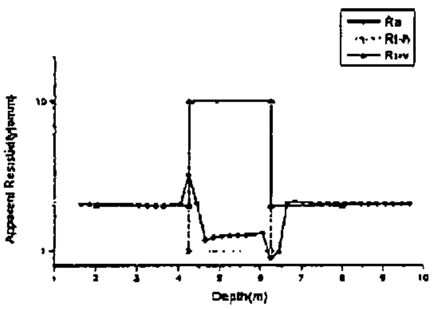

Fig 3c Lateral log

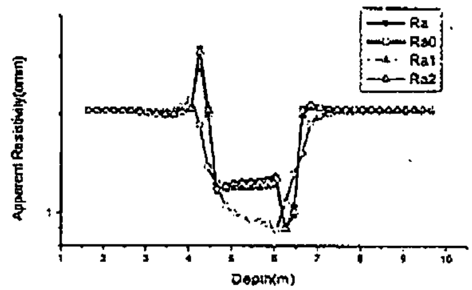

Fig 4c Lateral logs of different inversion iteration

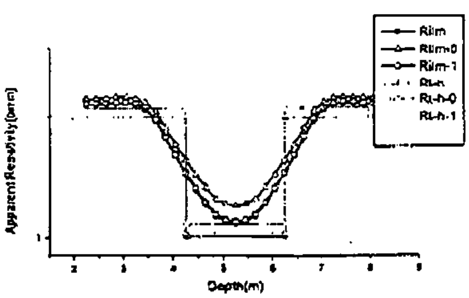

Fig 4a Inversion of induction log